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A TACTICAL PRESENT WEATHER SENSOR FOR AIR FORCE APPLICATIONS

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PHILLIPS LABORATORY
Directorate of Geophysics
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A Present Weather Sensor has been developed for Air Force tactical applications under a Phillips Laboratory Broad Agency Announcement to meet the more general requirement for "Automated Fixed/Bare Based Weather Sensors". The Present Weather Sensor design is based on techniques evolved over a period of time by HSS Inc for the automated measurement of visibility and precipitation. The prototype sensor is a compact, rugged, light weight, single-package instrument capable of measuring visibility and several precipitation parameters (i.e. precipitation type, intensity and rate of fall). Preliminary tests demonstrate that the performance of the tactical sensor is comparable to that of the performance of the highly regarded larger HSS Inc Present Weather Sensors.

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PREFACE

The meteorological instrument described in this report is designated as a tactical present weather sensor. It is both a visibility sensor and a precipitation sensor, capable of detecting and identifying precipitation, and measuring its rate-of-fall. The instrument was developed under a U.S. Air Force contract as potentially one of a suite of compact, lightweight, rugged, portable meteorological sensors that can be readily transported by cargo aircraft to any remote destination in the world and setup for immediate operation as a tactical weather station.

Dr. H.A. Brown of the Geophysics Directorate of Air Force Phillips Laboratory was the technical monitor of the program under which the development and performance evaluation of the tactical present weather sensor was performed. We express our deep appreciation to him for his unfailing support through the contract period.

Performance evaluation of the sensor was conducted at the Geophysics Directorate Weather Test Facility (WTF) at Otis ANGB on Cape Cod, MA. Mr. Ralph Hoar and Mr. Clyde Lawrence, stationed at the WTF extended the fullest possible cooperation and interest during the performance evaluation period, for which we gratefully thank them.

Data from the main data collection system at the Otis WTF is transferred to the Volpe Transportation Systems Center of the U.S. Department of Transportation in Cambridge, MA where it is systematically organized and processed for evaluation and distribution. HSS, Inc is indebted to Mr. Steve Abramson and Mr. David Hazen of that organization for providing us with files of data taken by the tactical present weather sensor and other meteorological sensors which were used by HSS, Inc to perform the sensor calibrations and evaluate its performance.

To Ms. Patricia Henckler we owe a debt of gratitude for her perseverance in editing and typing of the document.

1.0 BACKGROUND

The development of the tactical present weather sensor described in this report had its origin in an HSS, Inc response to the Phillips Laboratory Geophysics Directorate Broad Agency Announcement of 1990. The particular area of Air Force interest was entitled "Weather Impact on Air Force Mission". The specific goal addressed was "Automated Fixed/Bare-Based Weather Sensors" under the general topic of "Operational Weather Systems".

The sensor concept proposed to the Geophysics Directorate by HSS, Inc was based on techniques evolved over a period of years by HSS, Inc for the automated measurement of visibility and precipitation. Of particular importance was the experience derived from the development of a miniature airborne visibility meter. A brief history of the experience leading to the development of the tactical present weather sensor is sketched below.

1982-1983 - As a result of an unsolicited proposal, HSS Inc received a contract from the then Air Force Geophysics Laboratory (AFGL) to develop an experimental model Airborne Visibility Meter (AVM) for use on Unmanned Aerial Vehicles (UAV's). In this sensor, HSS Inc pioneered the use of Light Emitting Diodes (LED's) as the source of light for forward-scatter visibility sensors. This new approach eliminated the bulk and weight of a conventional lamp and chopper wheel thus allowing a reduction in size and weight of the sensor. At the same time it permitted source modulation and synchronous detection in the kilohertz range, well above any natural background modulation approach.

Upon completion of the AVM I development program, a potential commercial market was recognized for a ground-based visibility sensor based on the AVM I approach. Several models of ground-based sensors were subsequently developed, and hundreds of sensors are now seeing use in AWOS systems, military test ranges, highway fog monitoring, foghorn sounding systems and general meteorological applications.

1983-1984 - In this time period, HSS, Inc recognized that its ground-based visibility sensor, if equipped with digital electronics instead of analog electronics, could be adapted to present weather measurements (i.e., the measurement of: precipitation identity, intensity and rate of fall plus maintaining the measurement of visibility).

HSS, Inc proposed the development of such a sensor with the necessary software algorithms to AFGL. The result of the program was the successful development of a ground-based present weather sensor which is finding use both in commercial and military applications.

A U.S. patent application was made for the unique techniques employed in the present weather sensor. Subsequent to receiving a U.S. Patent, patents were applied for and granted in Canada and Germany.

1984-1985 - During this time period, HSS Inc developed a portable battery-powered present weather sensor (Model PW-403) for the U.S. Army WSML-ASL under a Phase I SBIR contract. A limited production run of 11 sensors was made under a Phase II program and delivered to WSMR in 1987. The WSMR sensor had many features that are desirable in a tactical present weather sensor. However, it had several drawbacks as a tactical present weather sensor: (1) it needed further reduction in size and weight, (2) it was not an inexpensive sensor and (3) it lacked a backscatter receiver, later found to be needed to improve precipitation identification.

1985-1987 - Under contract to AFGL, HSS, Inc developed a Phase II engineering prototype airborne visibility meter (AVM III) that had some precipitation monitoring capability in addition to the visibility measuring capability.

Also during this time period, HSS, Inc received a contract from AFGL to improve the precipitation identification performance of its ground-based present weather sensor. The result of this program was the addition of a backscatter receiver to augment the forward-scatter receiver. Precipitation identification was improved markedly.

1989-1990 - A Phase III contract was received from AFGL to undertake a considerable reduction in the size and weight of the Airborne Visibility Meter (with added precipitation measurement capability). A reduction in overall weight from 14 pounds to 4.4 pounds was achieved through the use of hybrid circuit technology. At the same time, the two separate packages (sensor head and power/control unit) of the AVM II were condensed to a single package in the production model sensor (AVM III).

The AVM III sensor has desirable size and weight characteristics for a ground-based tactical present weather sensor, but it has a configuration which would seriously impair its performance as a ground-based sensor. Further, the AVM III lacks a backscatter receiver which was found to aid in precipitation identification.

As an airborne sensor, the AVM III is mounted in the free air stream of its host aircraft vehicle. The atmosphere to be sampled, including aerosol particles, cloud droplets and precipitation are swept through the sample volume by the forward motion of the vehicle.

The sample volume of the AVM III sensor resides so close to the body of the sensor that in a stationary ground-based situation, the body of the sensor will inhibit the free flow of fog into the sample volume, and fully or partially shield the sample volume from precipitation depending upon the sensor orientation. These apparent limitations were dramatically confirmed during pre-flight ground-based testing at the Air Force Weather Test Facility at Otis ANGB on Cape Cod, MA.

Design, development and testing of the AVM series of sensors is discussed in Reference 1. HSS, Inc present weather measurement techniques may be found in References 2 and 3.

This report assumes the reader has a general familiarity with forwardscatter visibility sensors and with the HSS, Inc present weather measurement techniques. The reader who is not is referred to the references cited above.

2.0 TECHNICAL OBJECTIVES

The broadly defined objective of the program described herein was to achieve a compact, rugged, lightweight sensor package to fulfill an Air Force need for a tactical ground-based instrument capable of measuring visibility and several precipitation parameters: i.e., precipitation type, intensity and rate of fall. Detailed performance characteristics and physical size-weight limitations were not initially spelled out, but were expected to be optimized for the tactical sensor by the application of state-of-the-art practices and the injection of the experience of the Air Force and HSS, Inc participants in the program.

After the start-up of the contract specific design objectives were agreed upon in a series of meetings and discussions between HSS, Inc and Geophysics Directorate represenives. These objectives integrated the proposed HSS Inc design goals for the tactical present weather sensor with the concepts of the Geophysics Directorate for the complete tactical weather station. The final integrated design goals for the present weather sensor included both the physical characteristics of the sensor and its performance characteristics as presented in Table 1.

Table 1 (a). Design Goals for the Air Force Tactical Present Weather Sensor.

PHYSICAL CHARACTERISTICS

Weight (Maximum)	16 lb
Size	Minimum Size Necessary to Maintain Performance Equal to Larger Non-Tactical Present Weather Sensors
Configuration	(a) Include both forward and backscatter receivers (b) Single-Package Sensor (c) Overall Compact Shape Requiring a Minimum of Storage Space
Power Source	12 VDC (See Note 1)
Power Consumption	Minimize Power Consumption by Software Control of De-Icer Heaters and Window Heaters
External Sensor Data Logging	Accept up to five analog voltage signals from external meteorological sensors
Self-Test Features	Provide Remote Maintenance Monitoring on the maximum possible sensor functions

Note (1): Late in the contract the Air Force requirement was changed to 115 VAC line power.

Table 1 (b). Design Goals for the Air Force Tactical Present Weather Sensor.

PERFORMANCE CHARACTERISTICS

Visibility Measurements

Visual Range Coverage	10 m to 75 km
Measurement Error: at 10 km	≦ 10%
Measurement Error: at 2 km	≦ 2%
Measurement Time Constant	30 seconds

Atmospheric Extinction Coefficient (EXCO)

Range of Coverage	300 km^{-1} to 0.04 km^{-1}
Linear Dynamic Range	7500:1
RMS Noise (Nighttime)	≦ 0.02 km^{-1}
RMS Noise (Daytime)	≦ 0.03 km^{-1}

Stability of EXCO Zero Setting

Ambient Temperature Effects	≦ 0.02/km
Long Term Drift	≦/ 0.02/km

Precipitation Measurements

Detection Threshold: Rain	0.00001 in/min.
Detection Threshold: Snow (H_2O Equiv.)	0.000001 in/min.
Rain Rate (Maximum)	∿ 10 in/hr.
Rain Rate Accuracy	≦ 10%
Identifications:	L,R,S,P,NP
Intensities:	L–,L,L+
	R–,R,R+
	S–,S,S+
(Unidentified Precipitation)	P–,P

Maintenance

MTBF (Calculated)	18,000 hrs.
Calibration Check	6 months
Clean Windows	3 months
Remote Maintenance Monitoring	Comprehensive

Environmental

Temperature Range	-40°C to 50°C
Altitude	0 to 20,000 ft
Precipitation	All Weather
Humidity	0 to 100%

Table 1 (c). Design Goals for the Air Force Tactical Present Weather Sensor.

DIGITAL COMMUNICATION INTERFACE

Interface Type	RS-232C, (Full Duplex)
Optional	RS-422
Optional	RS-485

Selectable Parameters

Baud Rates (Any Two)	300, 600, 1200 2400, 4800, 9600
Bits per word	7 or 8
Parity	Even, Odd, None, Ignore on Receive
Stop Bits	1 or 2
Message Termination (Selectable)	CR, LF, CR-LF
Message Check Sum:	Selectable
Reporting Interval:	Programmable

(Response to poll, or Automatic at programmable intervals: e.g., 30 seconds to several minutes; 1 minute typical)

Message Content:

- Instrument Identification Number (Programmable)
- Reporting Interval (seconds)
- Daytime Visual Range (Miles or Kilometers)
- Atmospheric Extinction Coefficient (1/km)
- Precipitation Type
- Obstruction to Vision (Fog, Haze, None)
- Precipitation Amount (One Minute Interval)
- Temperature
- Remote Maintenance Flags

3.0 SENSOR DEVELOPMENT

3.1 Design Configuration

3.1.1 Forward Scatter Configuration

Todays state-of-the-art visibility sensors employ the forwardscatter measurement principle. Sensors employing that principle are called forwardscatter meters (FSM's). Almost universally, these sensors employ a central scattering angle in the range of 35 to 55 degrees.

The desirable features of FSM's are: (1) the convenience of their size, (2) they are much less costly and easier to maintain than integrating nephelometers and transmissometers, and (3) they have a far larger range of visibility coverage than transmissometers.

The undesirable features of FSM's are: (1) they do not measure the atmospheric extinction coefficient directly, which is the quantity required for determination of visibility, instead they measure an angular scattering coefficient, and (2) they sample only a very localized volume of the atmosphere.

The first of these undesirable features is overcome by the utilization of the forwardscatter meter principle. Published literature (e.g., References 4 and 5) has shown that FSM's operating in the range of scattering angles from 35 to 55 degrees provide a near constant relationship between their measurements of the angular scattering coefficient and the total scattering coefficient (i.e., scattering over all angles) for all natural hazes and fogs. This near-constant relationship allows a single calibration constant to be employed with FSM's to make accurate determinations of the total scattering coefficient in any fog or haze situation. Note, however, that the total scattering coefficient is the end result of this process, not the required atmospheric extinction coefficient.

In the visible and near-visible spectral regions, natural hazes and fog particles exhibit negligible amounts of absorption of light. Thus, for these spectral regions the total scattering coefficient and the atmospheric extinction coefficient are synonymous. This latter equivalence completes the linkage from angular scattering coefficient to atmospheric extinction coefficient via the total scattering coefficient, <u>but only for fog and haze situations.</u>

The localized measurement provided by FSM's is not a serious handicap for most applications since most weather phenomena takes place more or less uniformly on a geographic scale much larger than the distance to an observers horizon.

The FSM configuration was the obvious choice for the tactical present weather sensor configuration, especially since the HSS Inc present weather sensor techniques utilize that configuration and the design goals for the tactical sensor were in large part predicated on the extrapolation of HSS Inc experience with sensors of the FSM configuration. Nevertheless, some unanswered questions remained: what central scattering angle to employ, and how best to include a backscatter receiver in the overall configuration.

HSS, Inc experiments with various central angles for FSM's, beginning with the Model PW-403 Sensor followed by the VF-500 and PW-600 Sensors demonstrated that a central scattering angle of 45 degrees has one advantage over other central scattering angles; i.e., the calibration constant for snow is nearly the same as the calibration constant for fog and haze. This fact, plus scattered light considerations, led to the conclusion that the central scattering angle of the tactical present weather sensor would be 45 degrees.

Most FSM's favor the 35 degree end of the range of allowable scattering angles because of the inverse relationship between scattering angle and signal strength for all atmospheric phenomena; signal strength being greatest at 35 degrees and least at 55 degrees. A slight penalty is thus paid for operating at 45 degrees vs. the conventional 35 degrees.

The reference standard against which visibility sensors are calibrated is the visible light transmissometer. With the 45 degree scattering angle, a single calibration constant suffices to bring FSM readings into agreement with those of a transmissometer for haze fog and snow episodes. There is no scattering angle in the range of 35 degrees to 55 degrees that permits a single calibration constant to work simultaneously for rain and any of the other three obscuring phenomena, haze, fog or snow.

It must be accepted that in rain FSM's provide higher extinction coefficients, therefore lower visibility determinations, than do transmissometers. Because of diffraction by raindrops, an anomalous effect occurs in transmissometers that begs the question whether transmissometers or FSM's provide the more accurate readings in rain. Leaving that question aside, one may accept the lower visibility readings in rain because if they err they err on the side of safety for aircraft operations.

3.1.2 Backscatter Configuration

The HSS, Inc present weather measurement techniques are uniquely adapted to the FSM configuration. Whenever a precipitation particle passes through the sensor's sample volume its size and velocity are determined; the size is determined from the amplitude of the light pulse created by the passage and the velocity is determined from the duration of the pulse. The size and velocity information are collected in a matrix by the on-board micro-computer and are stored for a time interval (the measurement time period, usually one minute) adequate to provide a statistically significant and representative sample of particle sizes and velocities. Types of precipitation are identified from their "Signature" in the Precipitation Recognition Matrix. The "Signature" is the particle size/velocity distribution that is characteristic of each type of precipitation. Size/velocity distributions caused by non-hydrometeoric particles, noise spikes, flashing lights and insects are rejected by false alarm algorithms.

Wind effects can cause distortions of the signatures. HSS, Inc found (Reference 3) that the addition of a backscatter receiver aided considerably in producing correct precipitation identifications in windy situations. In this latter technique, the ratio of forward to backward scattering coefficient measurements are used for identification purposes. One or both methods are employed in HSS, Inc present weather sensors depending upon the particular application and climatology.

The Air Force need for accurate identification of precipitation type under all environmental conditions prompted the Geophysics Directorate personnel to require that a backscatter receiver be incorporated into the design of the tactical present weather sensor.

The term backscatter as applied here refers to light scattering at angles greater than 90 degrees. The particular backscatter angle of importance is that which optimizes the difference in the forwardscatter/backscatter ratio for various types of frozen precipitation vs. raindrops. This optimization occurs at scattering angles in the vicinity of 100 to 120 degrees where a saddle occurs in the raindrop angular scattering coefficient.

The backscatter receiver must necessarily be a detachable module for calibration purposes. Its obvious location for operational purposes is to be mounted centrally between the optical transmitter and forwardscatter receiver arms, facing the sample volume. In that position, the central backscatter angle is 112.5 degrees, midway in the optimum range of backscatter angles. A mount must also be provided in that vicinity for the calibration reference standard when in use. There is no conflict since the backscatter receiver must be moved to another location for its calibration check.

3.1.3 Sensor Package

Conventional FSM's and present weather sensors are packaged in two units, a sensor head and a power/control unit. The sensor head contains the optical transmitter and forwardscatter receiver (and a backscatter receiver in some types of HSS, Inc present weather sensors). Electronics associated with the transmitter and receiver(s) are also housed in the sensor head. Electronics associated with data processing and communications plus the electrical power and control modules are housed in the power/control unit.

One of the principle design goals of the program was the elimination of the power/control unit, to be achieved by consolidating its functions and hardware in the sensor head. This goal was to be achieved while maintaining the minimum possible dimensions for the sensor head and also while adding a backscatter receiver, backscatter receiver electronics, remote maintenance monitoring and a capability to accept analog signals from other meteorological sensors.

For the tactical sensor design it was never intended that the minimum dimensions stray far from those of the sensor head of the smallest ground-based HSS, Inc present weather sensor, the Model PW-600. The Model PW-600 has a 30 inch span from the extreme end of the optical transmitter to the extreme end of the forwardscatter receiver. (The PW-600 has no backscatter receiver).

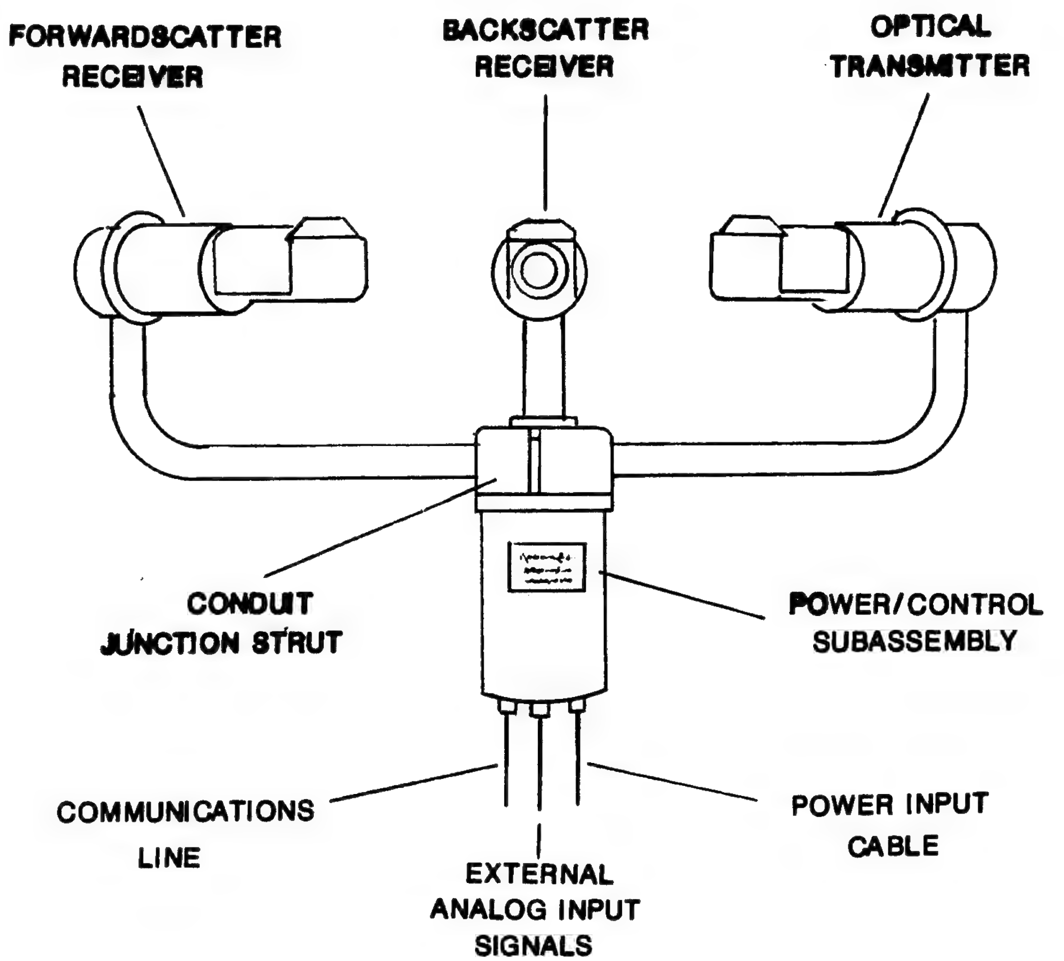
The minimum "wingspread" typified by the Model PW-600 sensor is dictated by hardware influencing factors (detector size, light source size and their optical projection systems) combined with a requirement that the illuminated sample volume be in the vicinity of 400 cm^3.

Past experience has shown that 400 cm^3 is a near-optimum size for HSS, Inc configured present weather sensors. A larger sample volume increases the probability of more than one precipitation particle being present at any one instant of time, thereby distorting the size and velocity measurements of an individual particle. A smaller sample volume has two disadvantages: (a) inhomogeneities in fog are averaged-out to a lesser degree, and (b) dynamic range requirements on the electronics becomes excessive due to a combination of factors.

Elimination of the power/control unit was achieved by miniaturizing much of the electronics. Figures 1 and 2 illustrate the final packaging that was accomplished by the overall electronic and mechanical design effort.

The tactical sensor design features, a central hub (the conduit junction strut) to which are attached the transmitter arm, forwardscatter receiver arm, backscatter

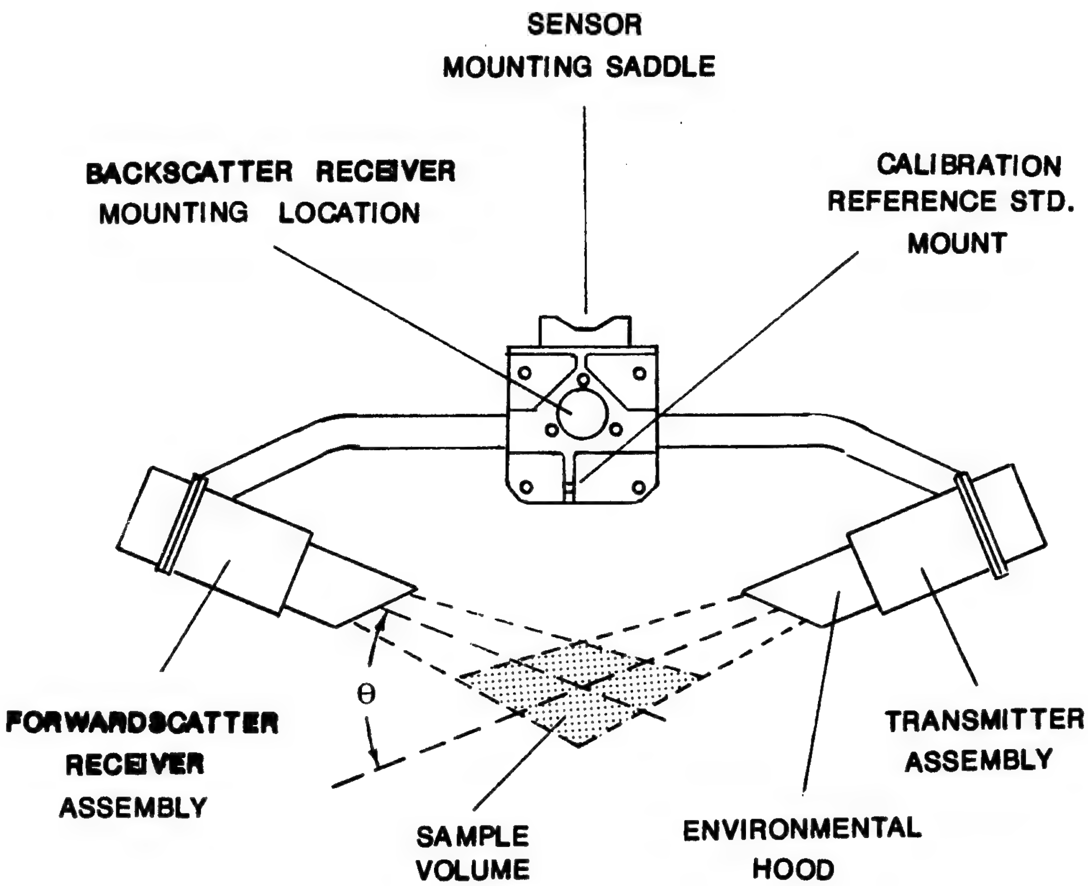
TACTICAL PRESENT WEATHER SENSOR



WINGSPAN	29 IN
WEIGHT (BATTERY POWERED)	10 LBS
(AC LINE POWERED)	15 LBS
POWER DEMAND (MINUS HEATERS)	6 WATTS

Figure 1 Front View of the Tactical Present Weather Sensor

TACTICAL PRESENT WEATHER SENSOR



FORWARDSCATTER ANGLE θ -------------------------- 45°

SAMPLE VOLUME ------------------------------------ 400 CM^3

Figure 2 Top View of the Tactical Present Weather Sensor

Minus the Backscatter Receiver Assembly

receiver assembly and a cylindrical enclosure which houses the power/control modules and the data processing/communication electronics. The conduit junction strut also serves as the point of attachment to whatever structure is used to support the sensor when in operation.

The wingspread of the tactical sensor is 29 inches. The total weight of the battery powered sensor is only 10 pounds, while the weight of an AC-powered tactical sensor is increased to 15 pounds by the addition of a transformer for heater power and added length of the power/control unit enclosure.

3.2 Electronic and Electrical Design

3.2.1 General

Miniaturization of the AVM III sensor discussed earlier in Section 1 of this report was accomplished by resorting to extensive use of hybrid circuitry in the electronics. The HSS, Inc program plan for a compact tactical present weather sensor originally called for elimination of the power/control unit by replacing many of the standard thru-hole circuit boards with circuit boards containing hybrid modules.

Once the program was underway, however, a study was conducted to review the possibility of utilizing surface mount circuit boards rather than hybrid circuit modules. That study concluded that if double-sided surface mount boards were utilized the desired goals could be achieved at much less expense than with hybrid circuits, especially for small sensor quantities.

The study also showed that the availability of companies providing surface mount services was far greater than the availability of those providing hybrid circuits, further, that the lead time for development of hybrid circuits was much longer than that for the development of surface mount boards. On the basis of these findings, the decision was made to employ surface mount circuit boards in the tactical sensor rather than the originally planned hybrid circuits.

3.2.2 Transmitter and Receiver Circuit Boards

In the HSS, Inc commercial Model PW-600 Present Weather Sensor, the space inside the cylindrical compartment extending down from the conduit junction strut is occupied by the transmitter and forwardscatter receiver circuit boards of the thru-hole type. The design plan for elimination of the separate power/control unit package called

for the power and control modules plus the data processing and communication electronics to be shrunk in size and placed in the cylindrical enclosure. The transmitter and receiver electronics were also to be reduced in size and moved out of the cylindrical enclosure into their respective transmitter and receiver housings.

The transmitter and receiver modules, the optical platforms on which they mount, and their housings were reconfigured to provide the small amount of space required by the addition of the transmitter and receiver circuit boards. No increase in size of the housings was needed.

The conventional thru-hole transmitter and receiver circuit boards of the PW-600 sensor each measure 2.5 x 5.0 inches in area. Surface mount technology permitted a reduction in size of the transmitter board to an area of 2.0 x 2.0 inches, and the receiver board to an even smaller area of 1.5 x 2.0 inches. The same surface mount receiver board is used in both the forwardscatter and backscatter receiver assemblies.

Had hybrid circuits been utilized in the transmitter and receiver electronics, the boards required by the hybrid packages and associated components would probably have occupied areas similar to those of the surface mount boards.

3.2.3 Data Processing and Communication

Full size HSS, Inc present weather sensors use a microprocessor integrated circuit and a large number of peripheral circuits to perform the required data acquisition, measurement computations and communications functions. The circuitry for all these functions is contained in two printed circuit boards, each 6.5 x 4.5 inches. Remote Maintenance Monitoring (RMM) and self-test functions require an additional circuit board of similar size.

The tactical present weather sensor achives the same functionality including Comprehensive RMM using one 3.25 x 4.5 inch surface mount circuit board with an attached "daughter" circuit board that is 2.4 x 3.0 inches in size. This very significant reduction in size is attributable to two factors: (1) the use of a single chip microcontroller, and (2) the use of surface mount components on the larger board.

For a substantial reduction in size of the data processing and communication electronics, selection of a microcontroller was critical. A microcontroller was sought which had the following integrated functions:

- Analog to digital converter (ADC).
- Analog multiplexer (at least 8 inputs).
- Interrupt controller capable of servicing interrupts from multiple sources.
- High speed counter-timers capable of:

(a) generating the 2 KHz square wave signal used by the sensor circuitry.

(b) triggering the analog to digital conversion of the sensor receiver signals in synchronism with the 2 KHz square wave.

- RS-232 compatible serial communications controller.
- Digital input/output ports to monitor and control sensor operation and to interface with an EEPROM which is used to store setup information and calibration constants.

The microcontroller selected was the INTEL 80C196. The 80C196 includes all the desired features, and is packaged in a one inch square 64-pin surface mount package. The one limitation of this controller is that the ADC has 10-bit resolution. Other HSS Inc present weather sensors use 12-bit ADCs. The 10-bit resolution means that there is a slight loss in measurement accuracy.

The IRED light source of the tactical sensor is modulated at a 2 KHz frequency in a manner identical to other HSS, Inc present weather sensors. Aerosol particles (fog, haze) present in the sample volume, or precipitation particles passing through it scatter the IRED light projected by the transmitter optics. Some of the scattered light is collected by the receiver optics and directed to photodiodes where it is converted to 2 KHz analog electrical signals. These analog electrical signals from the forwardscatter and backscatter receivers are converted to digital signals by the ADC function of the 80C196 microcontroller. Digital synchronous rectification and filtering are then performed using software algorithms to extract the received signals from the extraneous noise inherent in the electronics and background radiation.

The measuring process requires good differential accuracy from the ADC, but very little absolute accuracy. Long time-constant digital filtering of noisy signals actually increases the resolution at the weak end of the signal measurement range. As a result, the atmospheric extinction coefficients (EXCO's) measured by the tactical sensor have resolutions that match those of the HSS, Inc present weather sensors with 12-bit ADC's, however, the accuracy is slightly reduced at high visibilities. A visual range coverage of 10 meters to 75 kilometers is achieved in the tactical sensor vs. the 10 meters to 150 kilometer range of other HSS, Inc sensors.

Resolution in measuring the size of precipitation particles is also reduced by the use of a 10-bit vs. 12-bit ADC. However, determinations of precipitation rate and precipitation accumulation are based on measuring the sizes of many particles detected during the sample time period (typically one minute). The averaging of contributions from many particles reduces the effects of the lower measurement resolution just as

noise aids in reducing the effects for a steady state signal. Accuracy of particle size measurements for the smaller size particles is degraded to some extent; however, precipitation rates and accumulation are virutally unaffected because these phenomena are by far influenced by the larger size particles.

3.3 Temperature Sensor

HSS, Inc present weather sensors typically provide the ambient temperature as another measurement parameter. Ambient temperature can be used as an additional aid in determining the type of precipitation. For example, if the ambient temperature is 15°C or greater, the sensor software can be programmed to identify any precipitation as rain, or if the temperature is below -20°C to identify any precipitation as snow.

In some HSS, Inc present weather sensors, the temperature sensor has been located external to the sensor; in others it is mounted internally on the data acquisition board. Obviously, the external location is the superior site since it is unaffected by the heat generated internal to the sensor primarily by electrical components and heaters.

From the standpoint of convenience and cost, the internal location of the temperature sensor is preferred. When an internal temperature sensor is employed, its calibration must be performed when the sensor has reached its steady-state equilibrium condition between inside and outside temperature. The differential between the internal and external temperatures is then removed in software by an offset factor. Thereafter, that same differential factor is applied to whatever internal temperature is measured by the temperature sensor.

For most HSS, Inc present weather sensors, the internal temperature sensor has proved adequate for its purpose. An accuracy of 2°C to 3°C is achieved under most environmental conditions. An exception occurs during clear summer days with high sun elevation angles. Then the sun loading on the sensor causes greater than normal internal/external temperature differentials. However, under these circumstances the only identification error that could occur would be to identify snow as rain if snow occurred in summer, an extremely unlikely event.

Temperature sensor location experiments were performed with the tactical sensor in an attempt to find a suitable internal location. A temperature sensor was mounted first on the microprocessor board, then on the forwardscatter receiver board. Neither location proved satisfactory. Control of the de-icer heaters, located in the transmitter and receiver hoods, is a microcontroller function and was based on the ambient

temperature as measured internally. But, whenever the heaters were turned on the internal temperature in the power/control housing and in the receiver housing were raised by at least 5°C. As a result, the heaters were caused to cycle on and off.

When the use of an internal temperature sensor proved unacceptable an inexpensive external temperature sensor was devised. This sensor attaches to the external analog sensor port shown in Figure 1.

3.4 RMM and Self-Test Features

HSS, Inc had proposed to incorporate a limited number of Remote Maintenance Monitoring (RMM) features in the tactical present weather sensor. Early in the design phase of the sensor development it was recognized that many other RMM and self-test features could be added relatively easily at that stage whereas, if at some later time the Air Force decided that it wanted or needed more RMM features, a major redesign and upgrading effort would be involved.

This attractive possibility coupled with a reduced need for monitoring of external analog signals (see the following section) were sufficient for HSS, Inc to decide to incorporate an additional number of RMM and Self-Test maintenance features. The entire collection of maintenance features was then defined as Comphehensive Remote Maintenance Monitoring (CRMM). The title comprehensive is intended to imply that essentially all functions of the sensor are monitored for their operational status.

There is a distinction between the RMM and Self-Test maintenance features. For RMM tests, the sensor is programmed to perform a check of each RMM parameter (usually once a minute). The measured value of each parameter is then compared with a normal range of values for that parameter. If the measured value does not fall within that normal range, an alert/alarm status is incorporated into the data message.

Field 16 of each data message indicates the RMM status of the sensor. The three-character word comprising Field 16 contains some immediate diagnostic information: i.e., (1) are the windows contaminated sufficiently to warrant cleaning, and (2) has the sensor been restarted due to a power outage or for some other reason since the last RMM Command. If Field 16 indicates an RMM alert/alarm other than these two specific reasons, the operator or maintenance technician can obtain detailed diagnostic information by querying the sensor with the command "R?"

The Self-Test maintenance features of the tactical sensor monitors several functions in which diagnostic measurements are made, but out-of-tolerance behavior is not incorporated into the alert/alarm status of the data message. The diagnostic

measurements are, however, available to the operator upon sending the command "R?". The combined RMM and Self-Test features present in the tactical present weather sensor are listed below:

TACTICAL PRESENT WEATHER SENSOR: CRMM

- Optical Source Power
- Forward-Scatter Receiver Sensitivity
- Back-Scatter Receiver Sensitivity
- Transmitter Window Contamination
- Forward-Scatter Receiver Window Contamination
- Back-Scatter Receiver Window Contamination
- Power Supply Voltages
- Non-Volatile Memory Check Sum Test
- EPROM Check-Sum Test
- Restart Occurrence
- Sensor Sample Interrupt Verification
- RAM Read/Write Verification
- Register Read/Write Verification
- A/D Conversion Accuracy Check
- Input Voltage Check (Battery Check on DC Powered Sensors Only)
- Forward-Scatter Background Illumination Level
- Back-Scatter Background Illumination Level

3.5 External Analog Signals

The INTEL 80C196 Microcontroller accepts eight analog miltiplexed signals. Initially it was planned to provide the tactical present weather sensor with a capability of accepting analog signals from eight external meteorological sensors. However, as the Geophysics Laboratory concept for the complete tactical weather station began to evolve the need to provide the tactical present weather sensor with the eight analog channel monitoring capability diminished.

At the same time, the idea of providing additional RMM and Self-Test capabilities had surfaced. Eventually, a trade-off decision was made to reduce the external analog signal monitoring capability to three channels and to divert the five freed-up signal channels to additional RMM and Self-Test features.

The prototype tactical present weather sensor was equipped with one external connector port for interfacing with external analog signals. The only analog sensor connected to the port was an external temperature sensor as described in Section 3. of the report.

4.0 SENSOR PERFORMANCE

4.1 Evaluation Site

A comparison of the measurements made by the tactical present weather sensor with measurements made by other meteorological sensors was conducted to confirm the design goal performance of the tactical present weather sensor.

The intercomparison with other sensors was conducted at the U.S. Air Force Phillips Laboratory Weather Test Facility (WTF) at Otis Air National Guard Base (ANGB) on Cape Cod, Massachusetts. The WTF is equipped with a wide range of meteorological sensors that can be used for comparison and evaluation purposes. Several larger HSS, Inc present weather sensors (Model PW-402B) are in the complement of sensors located at that facility.

The tactical present weather sensor was first installed at the WTF in August 1993. During the winter of 1993/1994 it was temporarily moved to Colorado for a period of six weeks. After its return, the sensor continued to operate at the WTF through the present time (October 1994) except for a few occasions when it was returned briefly to HSS, Inc for the correction of minor hardware and software glitches.

As is the case with any new sensor design, the initial performance evaluation period was also used to establish preliminary calibration parameters. After the initial evaluation period was completed sensor performance was re-evaluted only at selected intervals, and calibrations were refined as deemed necessary.

Sensor performance has proven to be comparable to that of other HSS, Inc present weather sensors. This was a highly desirable result given the well-documented performance of other HSS, Inc present weather sensors and the esteem with which they are held by those whose organizations own and operate them.

At the WTF, the data messages from the tactical present weather sensor are recorded by a WTF data logging system that is common to all the meteorological sensors being monitored at that site. Raw data from that logging system is sent to the Volpe National Transportation Systems Center (TSC) for archiving and processing in accordance with the requirements of the Geophysics Directorate of the Phillips Laboratory.

The data presented in the illustrations that follow was kindly furnished to HSS Inc by the TSC on diskettes containing zipped files. These files contained raw data messages from the tactical present weather sensor and other HSS, Inc present weather sensors, plus real-time corrected transmissometer extinction coefficients and rainrate measurements.

For convenience of notation in the illustrations, the tactical present weather has been given the designation Model VPF-730, or sometimes Model VPF-700.

4.2 Rainrate Observations

4.2.1 Comparison Techniques

Automated observations of rainrate are typically evaluated by two methods. One method compares the sensor rainrate, averaged over one-minute sample-time-periods, with the rainrate measured by a reference sensor having similar time resolution. This method can be quantitative or semi-quantitative depending upon the relative co-location of the two sensors.

The second method compares the measured rainfall accumulation for the two sensors during an entire rain episode or rain shower. In this case, an assumption is made that if the accumulated amounts of rainfall agree then the instantaneous rainrates throughout the episode must agree, the whole being equal to the sum of its parts.

4.2.2 Temporal Observations

Figure 3 compares rainrate measurements of the tactical present weather sensor with those of a sensitive weighing-rain-gauge developed by the Geophysics Directorate of the Phillips Laboratory. The weighing rain gauge is more sensitive than tipping bucket rain gauges and has time resolution comparable to the present weather sensors.

The tactical sensor and the weighing rain gauge are separated by 600 feet at the WTF, which explains the minor differences in temporal behavior of the two rainrate histories as well as the differences in some of the peak amplitudes. At times, the peak amplitudes measured by the tactical sensor exceed those of the weighing rain gauge, at other times the reverse situation occurs.

Figure 4 presents a portion of the same data that is shown in Figure 3, but with expanded scales to aid in comparing the detail of each sensor's rainrate history.

Figure 5 is a comparison of the rainrate measurements made by the tactical present weather sensor with those of two larger model HSS, Inc present weather sensors (Model PW-402B). The three sensors are located within 50 feet of each other at the WTF. Minor differences occur between the peak rainrate amplitudes as measured by the three sensors, but because of their close proximity to each other there are essentially no differences in their temporal behavior.

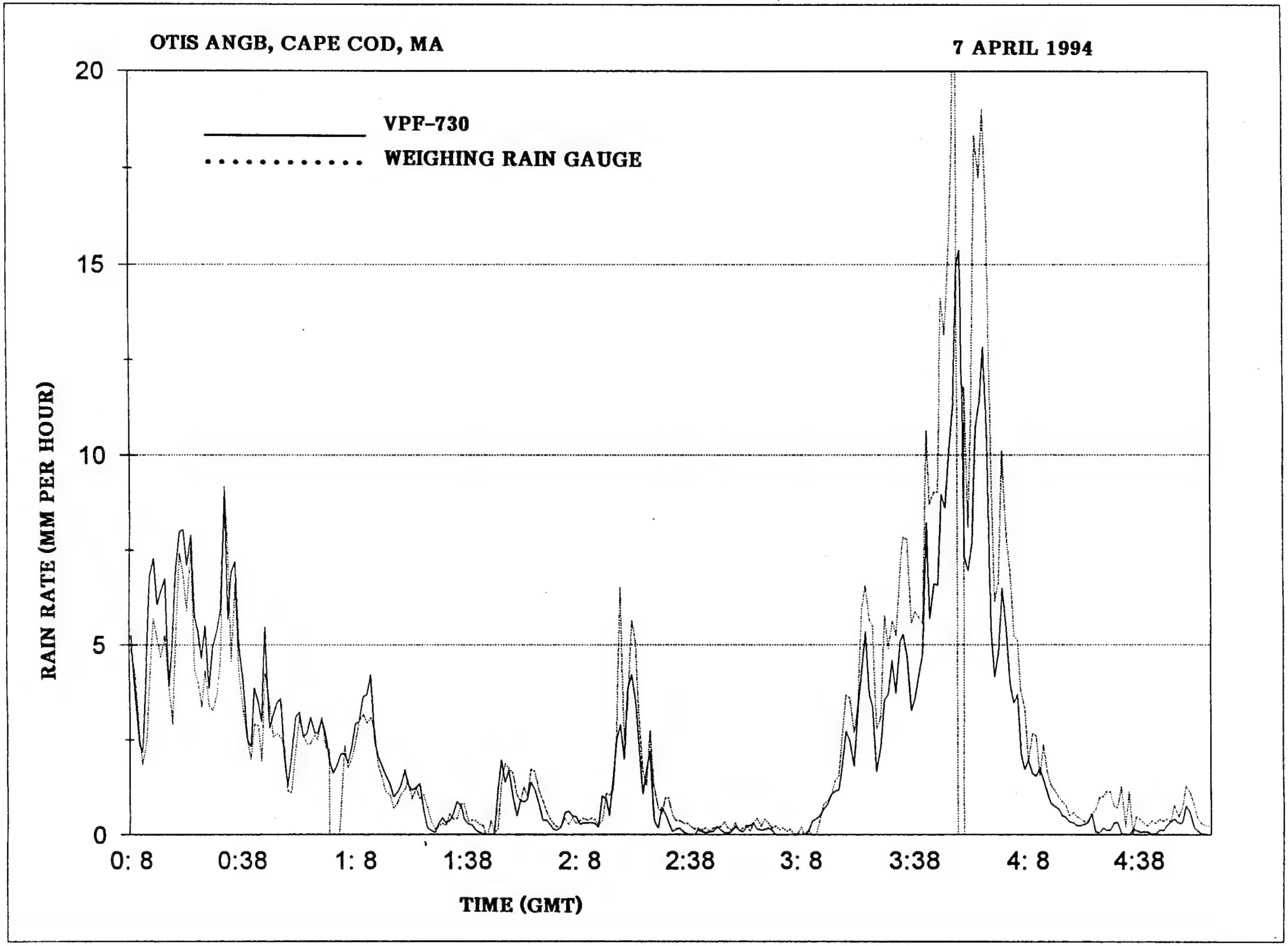


Figure 3 Comparison of Rain Rate Measurements Tactical Present Weather Sensor and Weighing Rain Gauge, 7 April 1994.

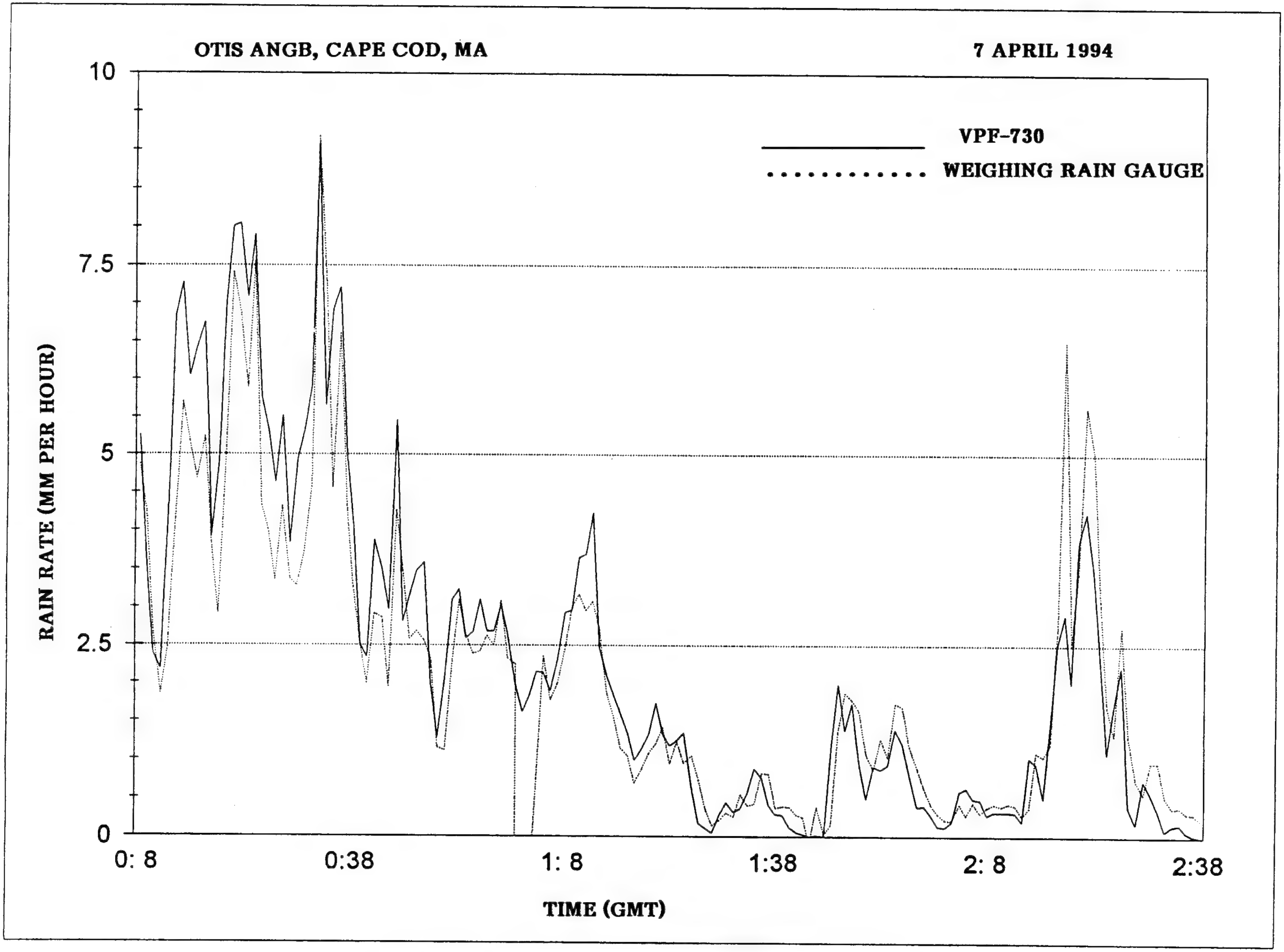


Figure 4 Previous Figure with Expanded Scales

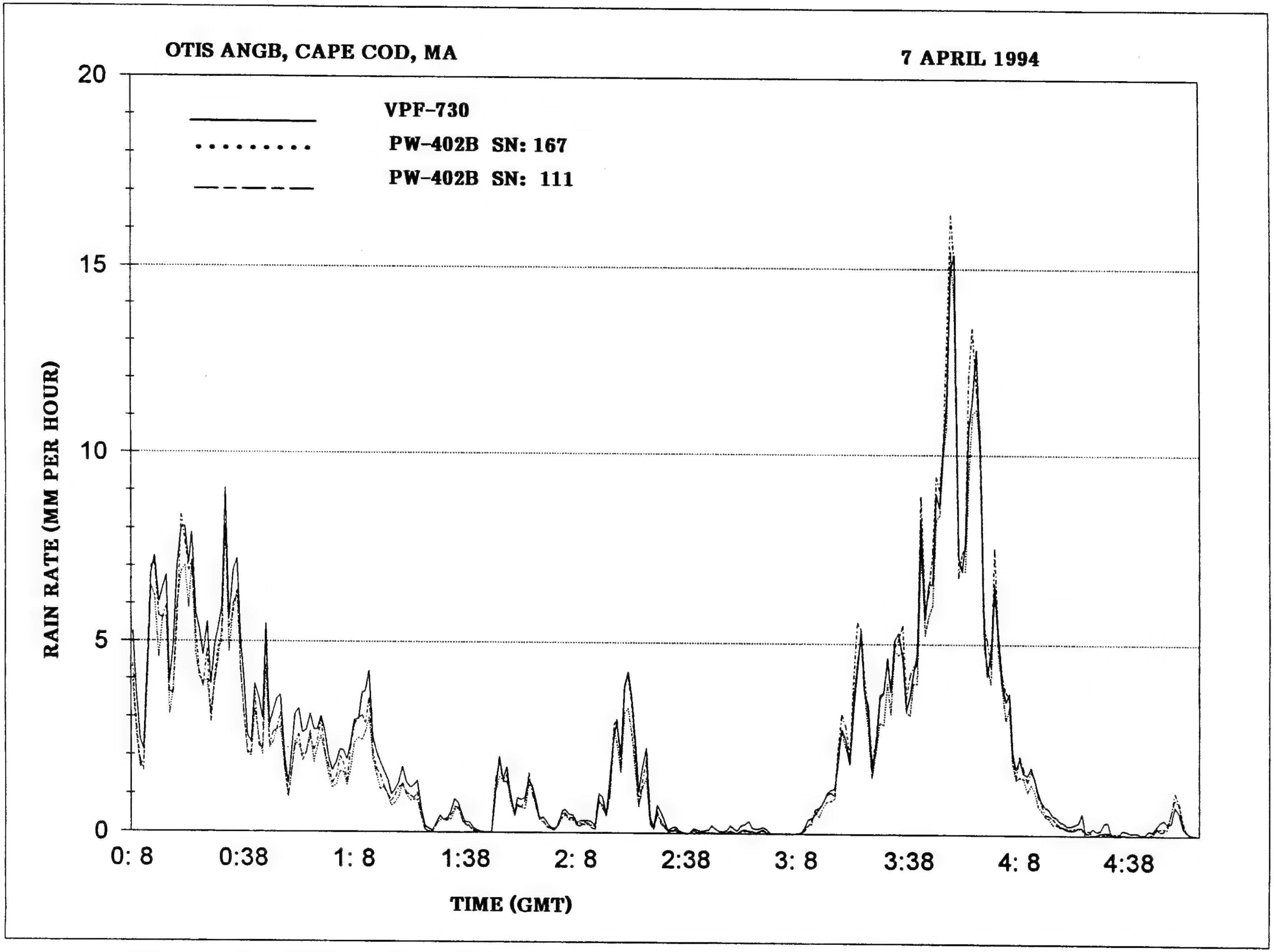


Figure 5 Comparison of Rain Rate Measurements by three HSS Inc Present Weather Sensors, 7 April 1994.

4.2.3 Rain Accumulation Observations

A comparison of rain accumulation measurements was made early-on in the performance evaluation of the tactical present weather sensor by David Hazen of the Volpe National Transportation Systems Center. He compared the measurements of the tactical present weather sensor (VPF-730) with those of the weighing rain gauge (WRG) and an HSS Inc Model PW-402B Present Weather Sensor for a number of rain showers in early to mid-September 1993. His results are given below:

RAINFALL ACCUMULATION (INCHES)

RAIN EPISODE DATE	VPF-730 S/N 001	WRG	PW-402B S/N 111
8 Sept. 1993	0.13	0.14	.10
10 Sept. 1993	0.36	0.33	.27
16 Sept. 1993	0.26	0.26	.24
17 Sept. 1993	0.27	0.48	.31
18 Sept. 1993	0.17	0.21	.15

There is fairly good agreement between the meaurements of tactical present weather sensor and the weighing rain gauge except for the measurement on 17 September. It is possible that the variance in measurements on that date can be attributed to the separation (600 ft) between the two sensors and the strength of the shower being somewhat localized. The measurement made by the Model PW-402B sensor on the same day seems to bear out this argument.

A linear regression analysis performed on the above data, omitting the measurements made on 17 September, yielded the following results:

	VPF-730 VS WRG	PW-402B VS WRG
Correlation Coefficient (r)	0.979	0.971
Best Fit Line Slope	1.249	.953
y-Intercept	(-).063	(-).034

From the results of the linear aggression analysis the following tentative conclusions were reached:

A. The rainrate calibration parameter for the VPF-730 should be reduced by the factor (1.000/1.249).

B. Using the square of the Correlation Coefficient (r^2) only 5.2% of the variability between the VPF-730 and WRG measurements can be associated with errors or untested factors.

C. The weighing rain gauge has a zero offset, or time lag, in its initial response (probably associated with evaporation or wetting).

As a result of Conclusion A, the rainrate calibration parameter for the tactical present weather sensor was adjusted downward by the appropriate amount.

4.3 Fog Observations

As previously mentioned, the reference standard by which nearly all visibility sensors are calibrated is the visible light transmissometer. Furthermore, such calibrations are invariably made using fog episodes as the operational environment. There are several good reasons for this approach: (1) transmissometers measure the atmospheric extinction coefficient - - - which is the physical quantity required for application of Koschmieder's Law of Contrast Reduction and Allard's Law of Point Light Visibility, (2) fog represents the severest natural obscurant to visibility, and thus the greatest threat to safe aircraft and highway operations, and (3) the accurate operating range of most transmissometers is restricted to fog and heavy haze conditions (Reference 6).

The WTF at Otis ANGB is equipped with several FAA approved transmissometers. In particular, it has two transmissometers whose baselines intersect at right angles at their midpoints to form a cross. One transmissometer (T500) has a 500-foot baseline oriented east/west; the other transmissometer (T300) has a 300-foot baseline oriented north/south. Visibility sensors that are to be subjected to performance evaluation and/or to be calibrated are clustered near the crossover point of the two transmissometer baselines to optimize the comparison conditions.

Calibration of a visibility sensor requires a scatterplot comparison of measurements made by the sensor under test with those of a transmissometer. Such a comparison is shown in Figure 6 for the tactical present weather sensor (VPF-700) and the T500 transmissometer. A best-fit straight line is then made to all the data points using a linear regression calculation. The slope of the best-fit line (and the scatter in the data points) determine the accuracy of the test sensor calibration; a well-calibrated sensor must have a slope of unity. If the slope is not unity, then the reciprocal of the slope is applied to the sensor calibration constant to establish the correct calibration constant for the sensor.

Each data point shown in Figure 6 represents a one-minute average of five measurements by the T500 transmissometer taken at 12-second intervals, and four measurements by the tactical present weather sensor taken at 15-second intervals.

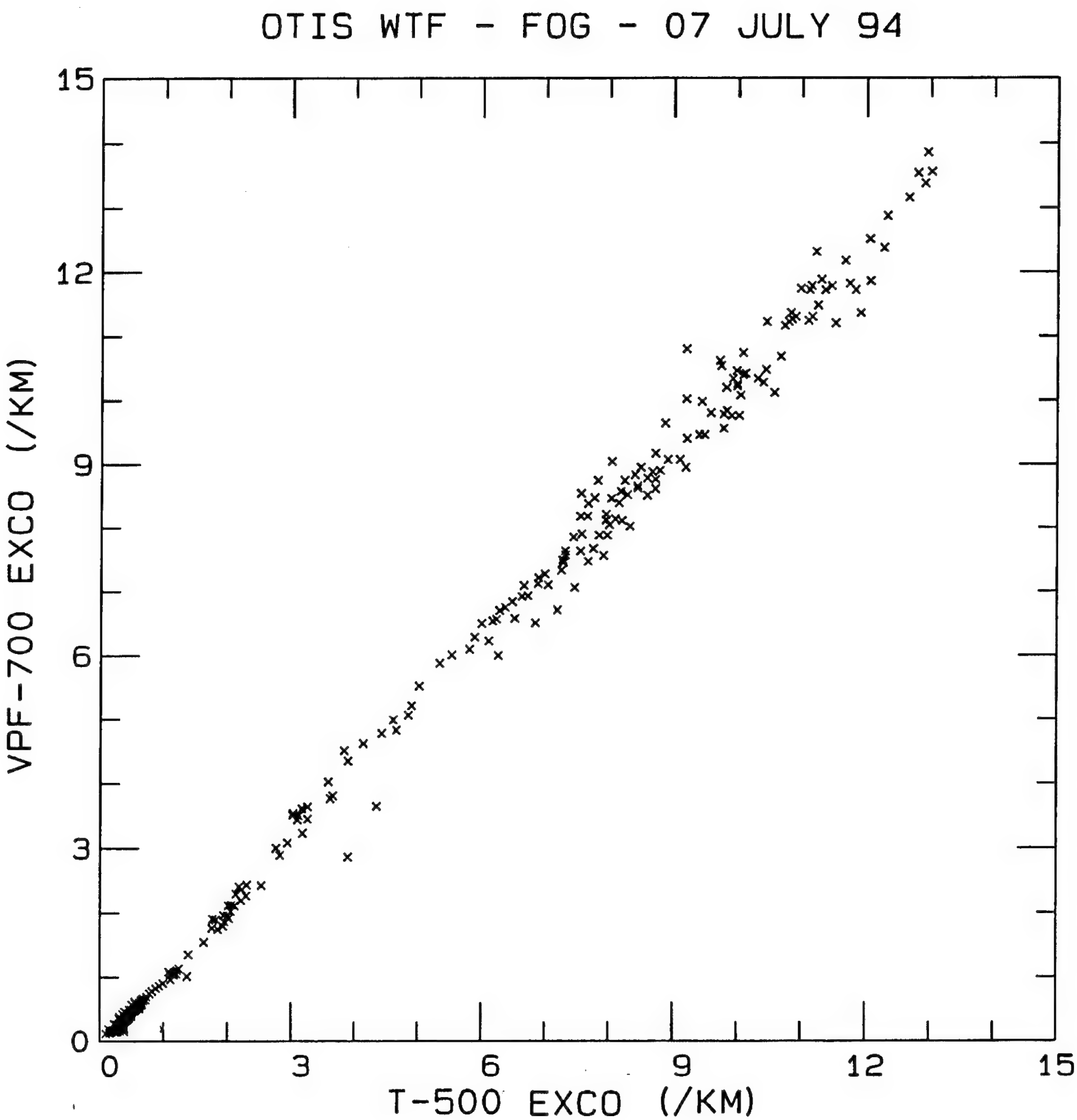


Figure 6 Scatterplot of VPF-700 vs. T500 Measurements; Fog Episode of 7 July 1994.

Fogs can be very non-homogeneous. Sensor calibrations and/or performance evaluations are obviously best carried out under uniform fog conditions. One test for uniformity that can be applied is a comparison of measurements made by the T500 and T300 transmissometers. If the two measurements disagree by more than say 5 percent (or 10 percent depending upon the test criteria) then measurements by all sensors for that particular sample time period are excluded from any evaluation.

Time and budget constraints did not permit the application of fog-uniformity tests to the scatterplot data for the fog episode of 7 July 1994 shown in Figure 6, nor to any of the scatterplot figures which follow.

Judging by the tight clustering of data points around a straight line of slope near unity, the fog episode of 7 July 1994 was a fairly homogeneous fog. By the same criteria, the fog episode on 9 July 1994 (see Figure 7) was less homogeneous. Also, the fog episode of 9 July 1994 produced a best-fit straight line of slope less than unity whereas the best-fit straight line to the data of 7 July gave a slope slightly greater than unity.

A slight wandering of slopes of best-fit straight lines in comparison measurements between forward-scatter visibility sensors and transmissometers is a well-documented phenomenon (see Reference 7). That study included HSS, Inc forward scatter meters plus those of other manufacturers. Slope changes from one fog episode to another is characteristic of all forward scatter meters. Another finding of that study is short term slope changes during a single fog episode. This latter phenomena is manifest in the fog episode data of Figures 8 and 9. The authors of that study could not convincingly correlate the changes of slope with any identifiable mechanism.

4.4 Precipitation Observations

Figures 10 and 11 continue the comparison of extinction coefficient (EXCO) between the tactical present weather sensor and a transmissometer, this time for snow and rain episodes. For these illustrations, the 300 foot baseline transmissometer (T300) used as the comparison standard.

Figure 10 is a scatterplot of data taken during a snow episode on 18 March 1994. Broadening in the scatter of data points as seen here is typical of precipitation episodes. In this instance, a best-fit straight line through the data points would produce a slope slightly greater than unity.

A point made earlier in this report indicated that a central scattering angle near 45 degrees for the sensor would produce a slope of unity in haze and snow if the sensor is calibrated to have a slope of unity in fog. Since a central scattering angle of 35 degrees gives a slope less than unity for snow episodes, the data shown in Figure 10 suggests

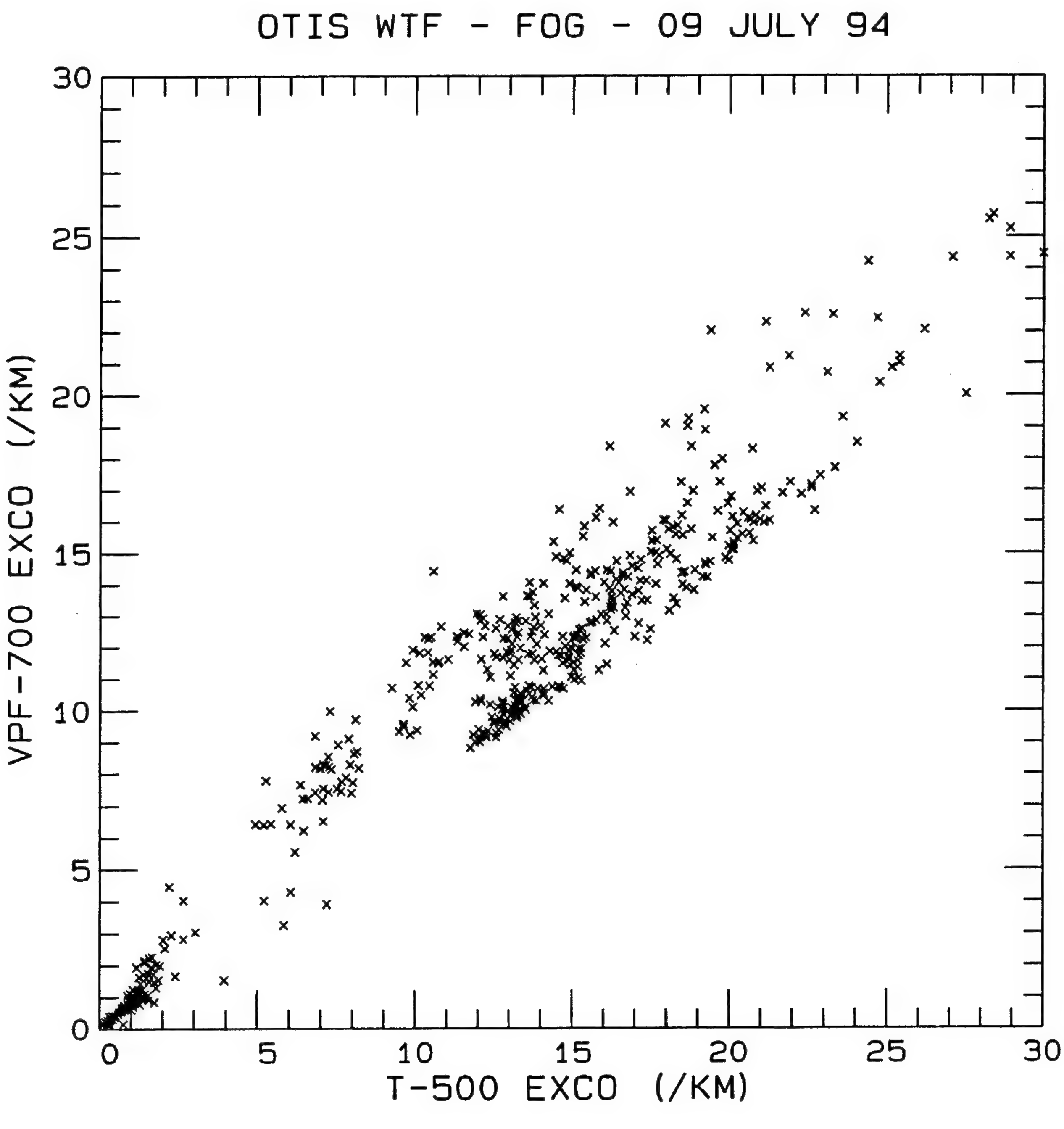


Figure 7 Scatterplot of VPF-700 vs. T500 Measurements; Fog Episode of 9 July 1994.

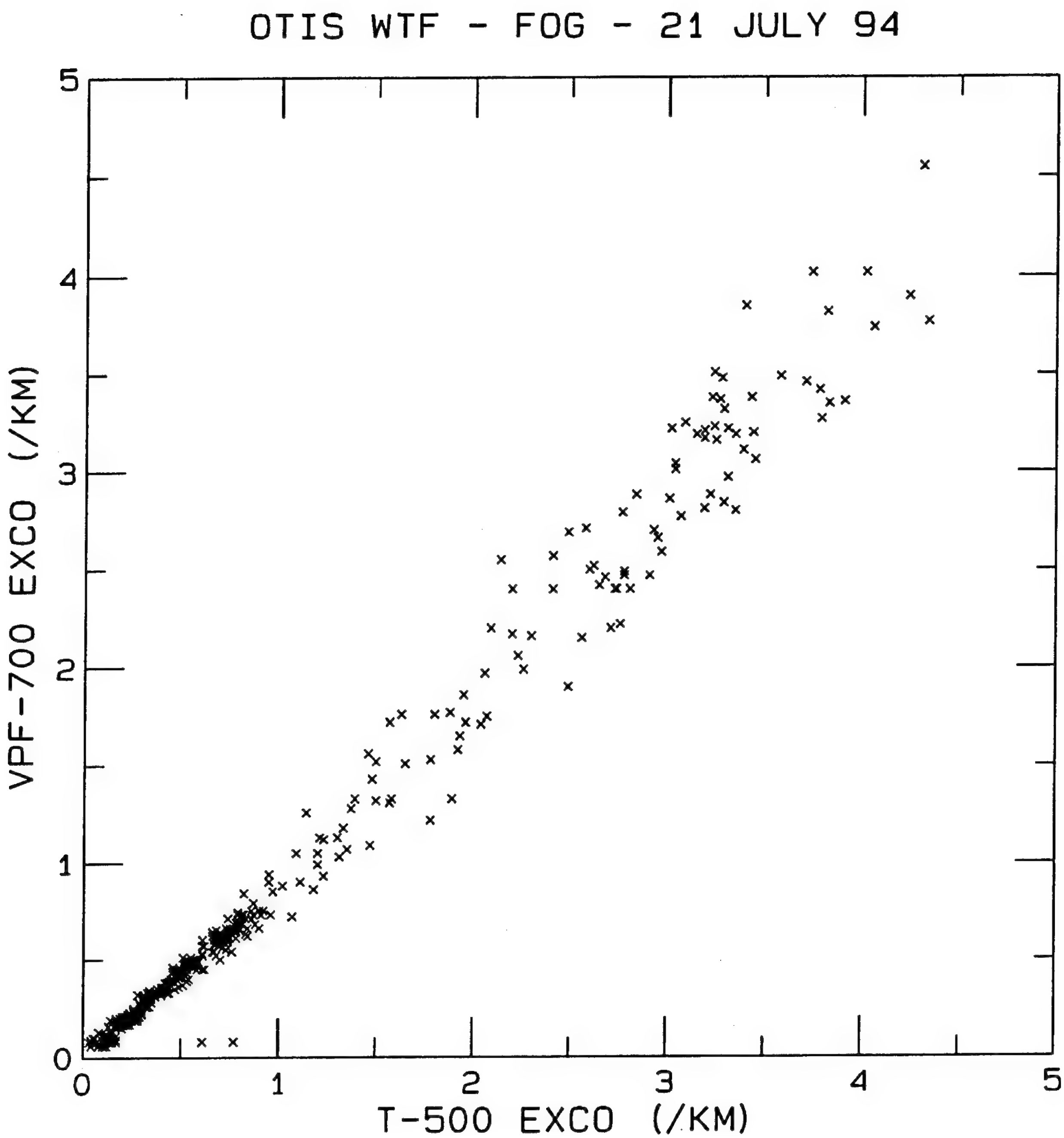


Figure 8 Scatterplot of VPF-700 vs. T500 Measurements; Fog Episode of 21 July 1994.

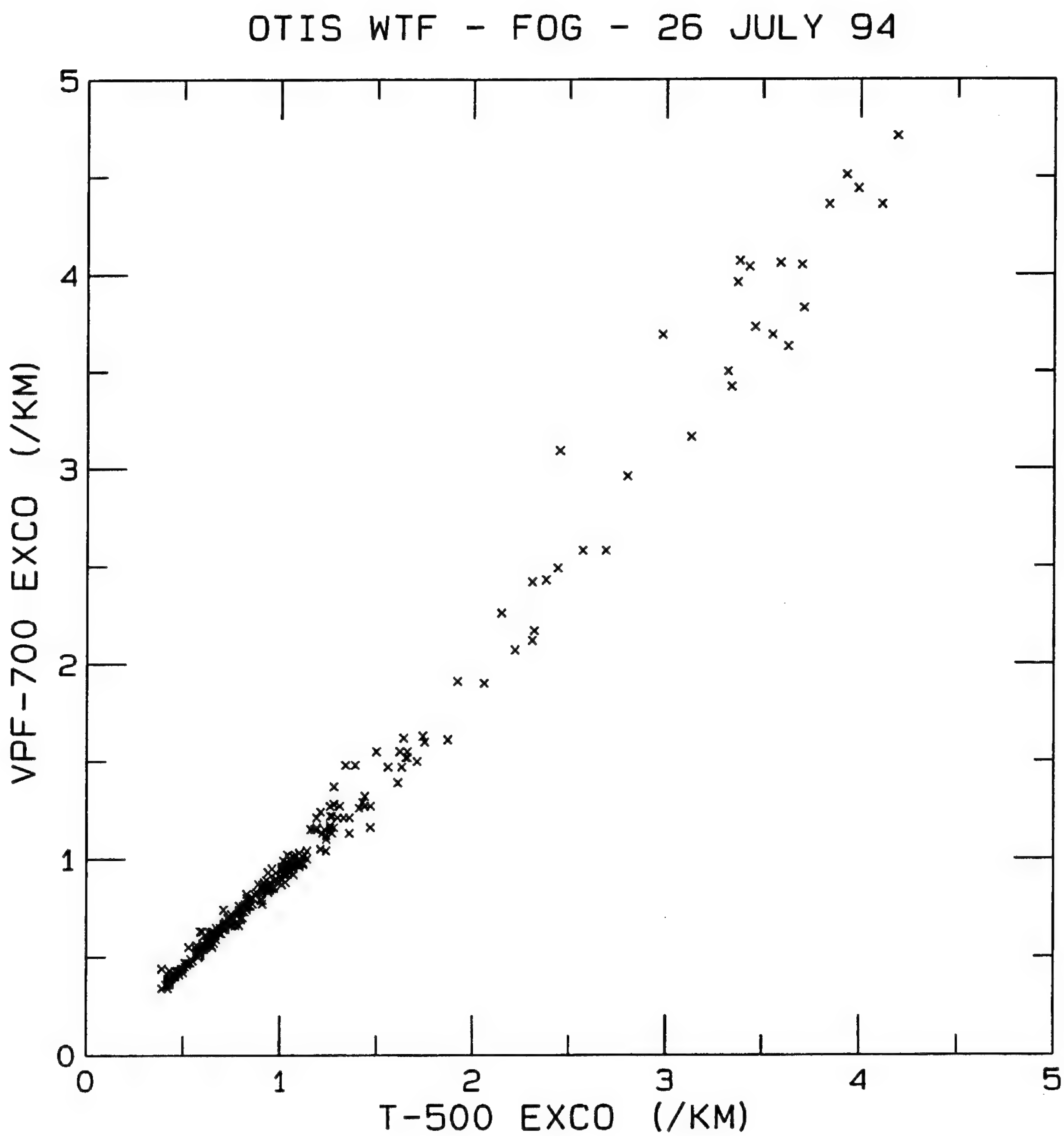


Figure 9 Scatterplot of VPF-700 vs. T500 Measurements; Fog Episode of 26 July 1994.

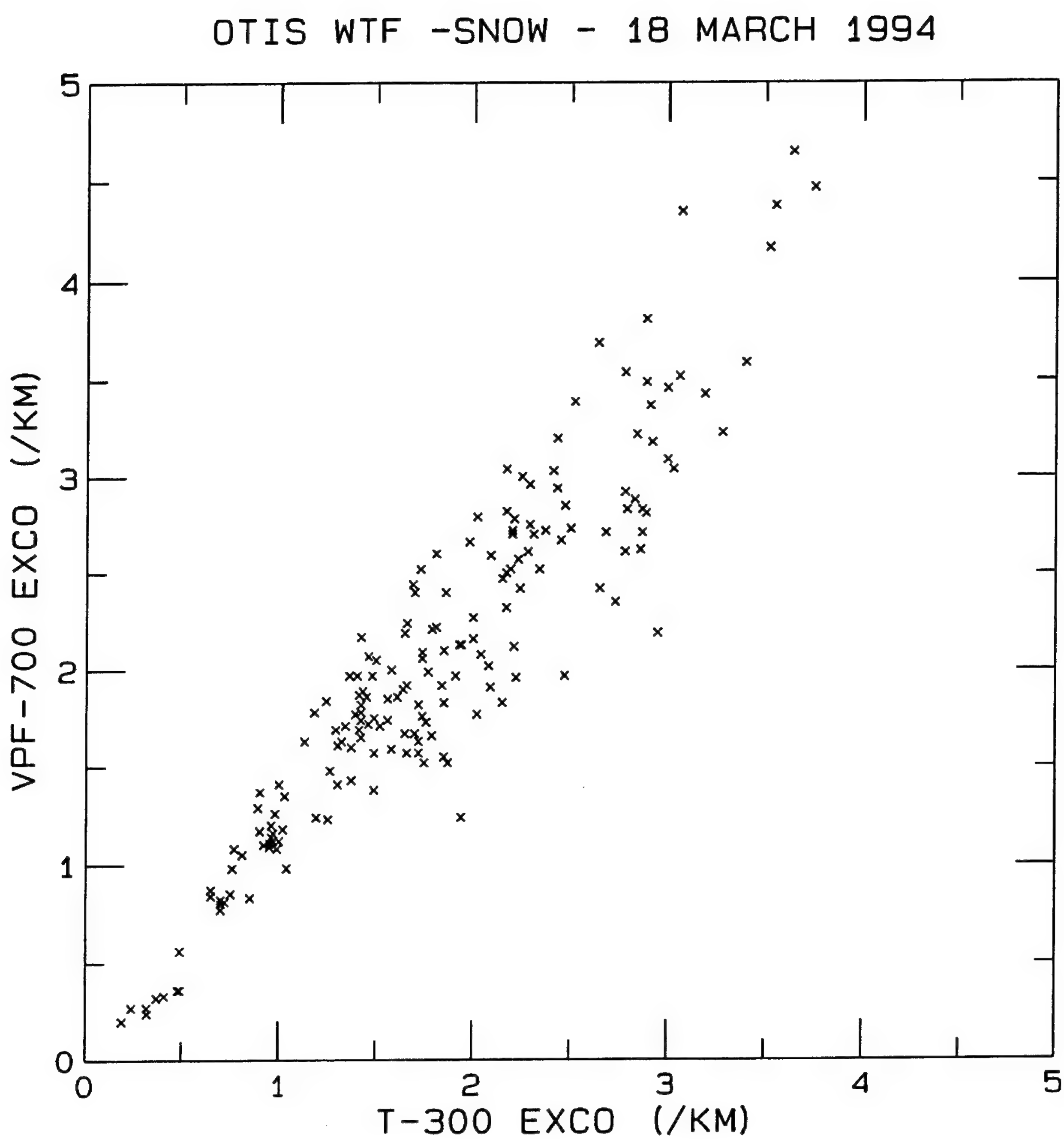


Figure 10 Scatterplot of VPF-700 vs. T-300 Measurements; Snow Episode of 18 March 1994.

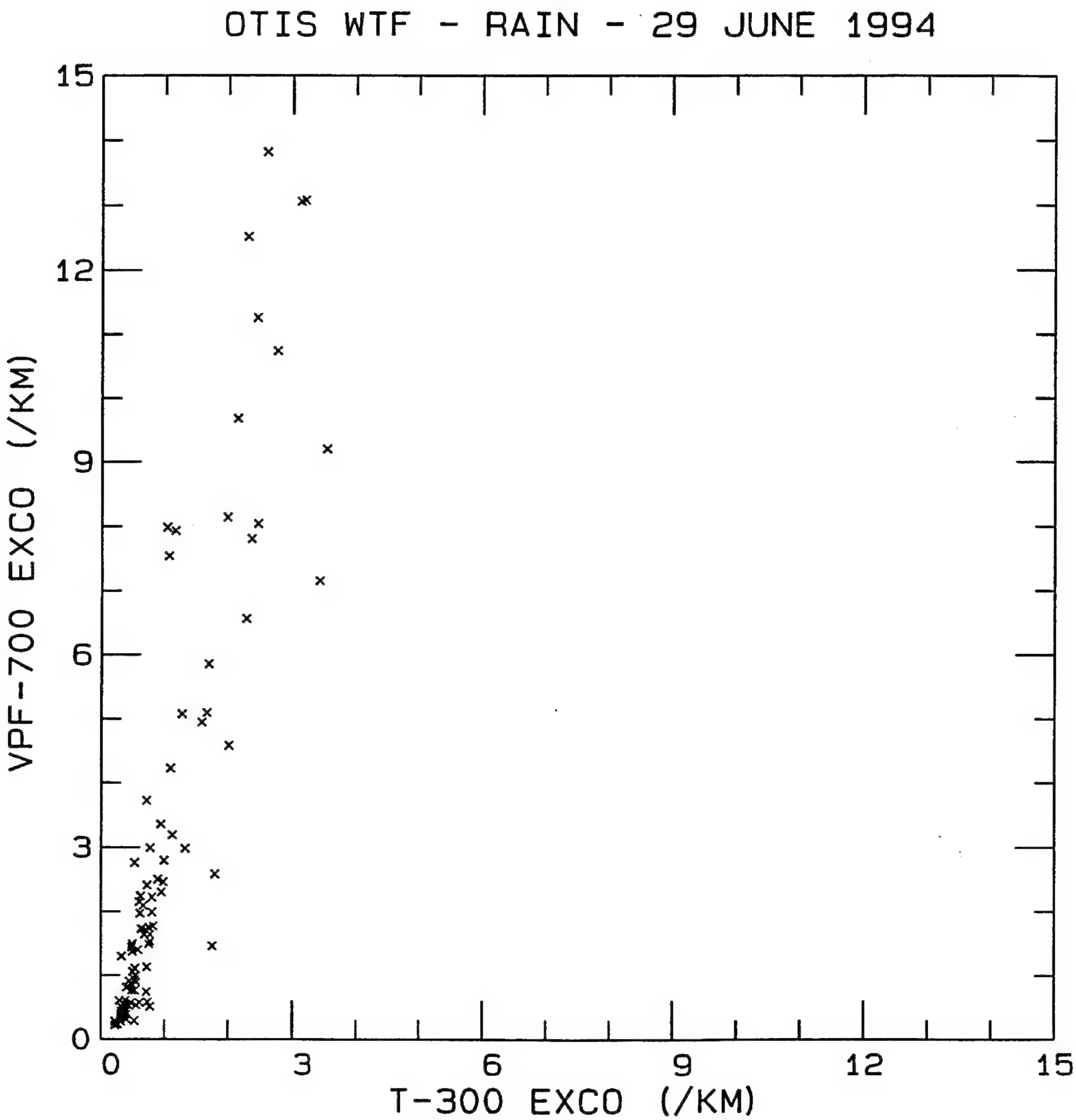


Figure 11 Scatterplot of VPF-700 vs. T-300 Measurements; Rain Episode of 29 June 1994.

that the optimum central scattering angle might be slightly less than 45 degrees. This result should be confirmed by the measurement of slopes for many snow episodes.

Figure 11 is a scatterplot of measurements taken during a heavy rain episode on 29 June 1994. The distinct feature of this scatterplot is the high slope (~ 3.7) of a best fit straight line, if it were drawn through the data points.

Another point made earlier in the report was that there is no central scattering angle that will produce a slope of unity for both fog and rain episodes.

If it is desirable that the tactical present weather sensor provides atmospheric extinction coefficient in rain that are equivalent to those which a transmissometer would measure, then the tactical sensor can be called upon to produce a transmissometer equivalent extinction coefficient (TEXCO) in each of its data messages.

HSS, Inc present weather sensors have the unique capability of producing TEXCO determinations. This capability requires only that the following procedural steps be taken: (1) with the tactical present weather sensor measure EXCO vs. rainrate (h) for a number of rain episodes extending from light rainfall to very heavy rainfall an example of which is shown in Figure 12, (2) develop a power law fit, Ah^n, to the EXCO vs. rainrate data, and (3) utilize an established power law relation for the transmissometer EXCO vs. rainrate, Bh^m, which can be found in published literature.

The desired transmissometer equivalent extinction coefficient is then determined by the following expression

$$\text{TEXCO} = \text{EXCO} - (Ah^n - Bh^m)$$

The suitable expression for TEXCO was not derived for the tactical present weather sensor, being beyond the scope of the present program.

4.5 Intercomparison of Present Weather Sensors

Since one of the goals of the program was the retention of the performance of the larger HSS Inc present weather sensors it is of interest to continue the intercomparison of sensor data that began in Section 4.2. Figures 13 and 14, give further examples of the close agreement between the measurements of the tactical present weather sensor and a larger Model PW-402B Sensor (PW67).

Figure 13 compares rainrate measurements between the two sensors for a rain episode on 7 April 1994. Note that the VPF-700 measurements are in mm/min while the rainrate measurements are in inches/min., and that .012 inches equals 0.305 mm.

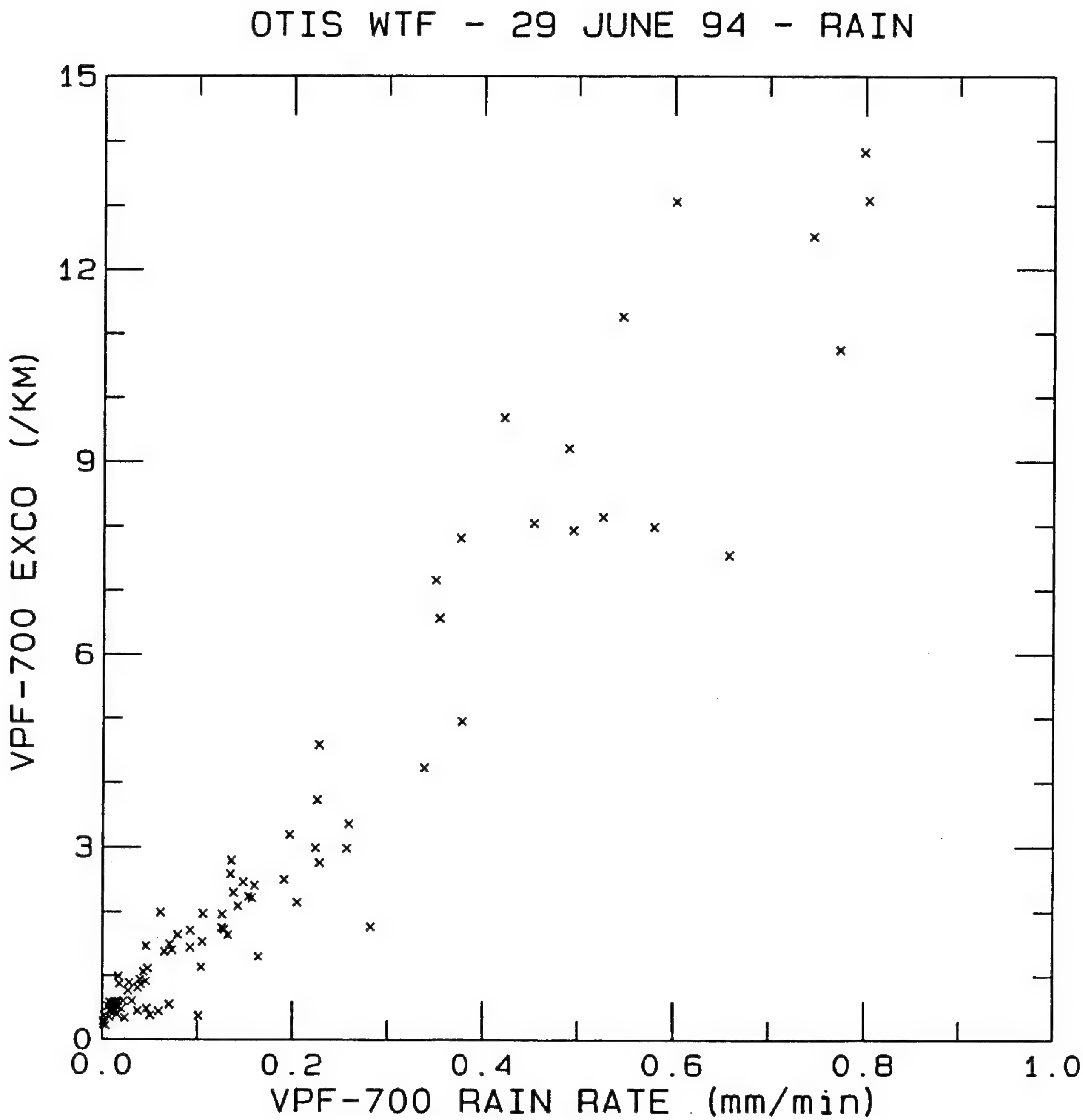


Figure 12 VPF-700 Plot of Atmsopheric Extinction Coefficient vs. Rainrate.

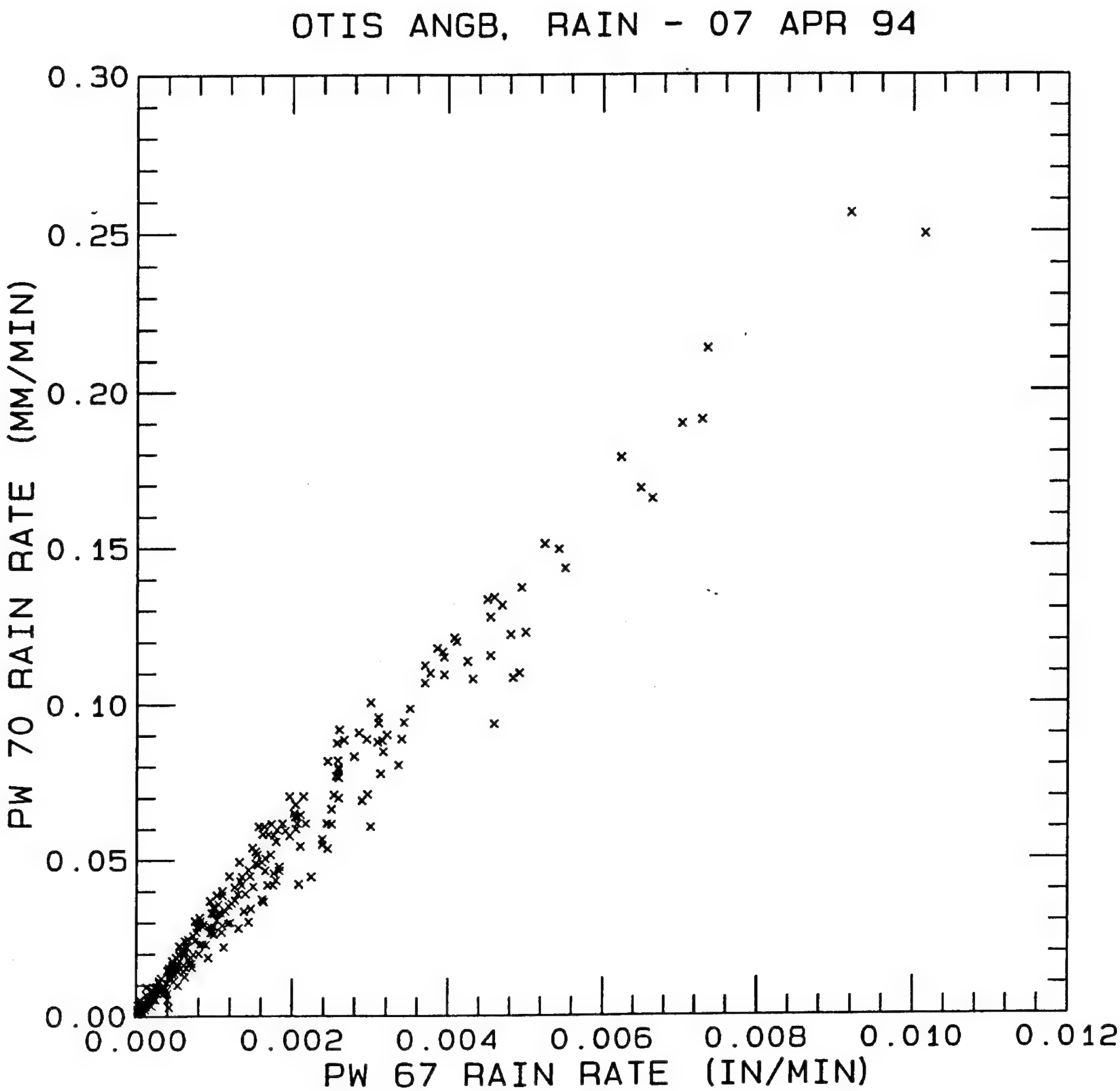


Figure 13 Comparison of Rainrate Measurements; VPF-700 vs. PW67; 7 April 1994.

Figure 14 compares the EXCO measurements btween the two sensors during that same rain episode. The slope of a best fit line though the data points, if drawn, would be less than unity. That is to be expected since the central scattering angle for the PW67 sensor is 35 degrees vs. the 45 degrees central scattering angle of the tactical present weather sensor.

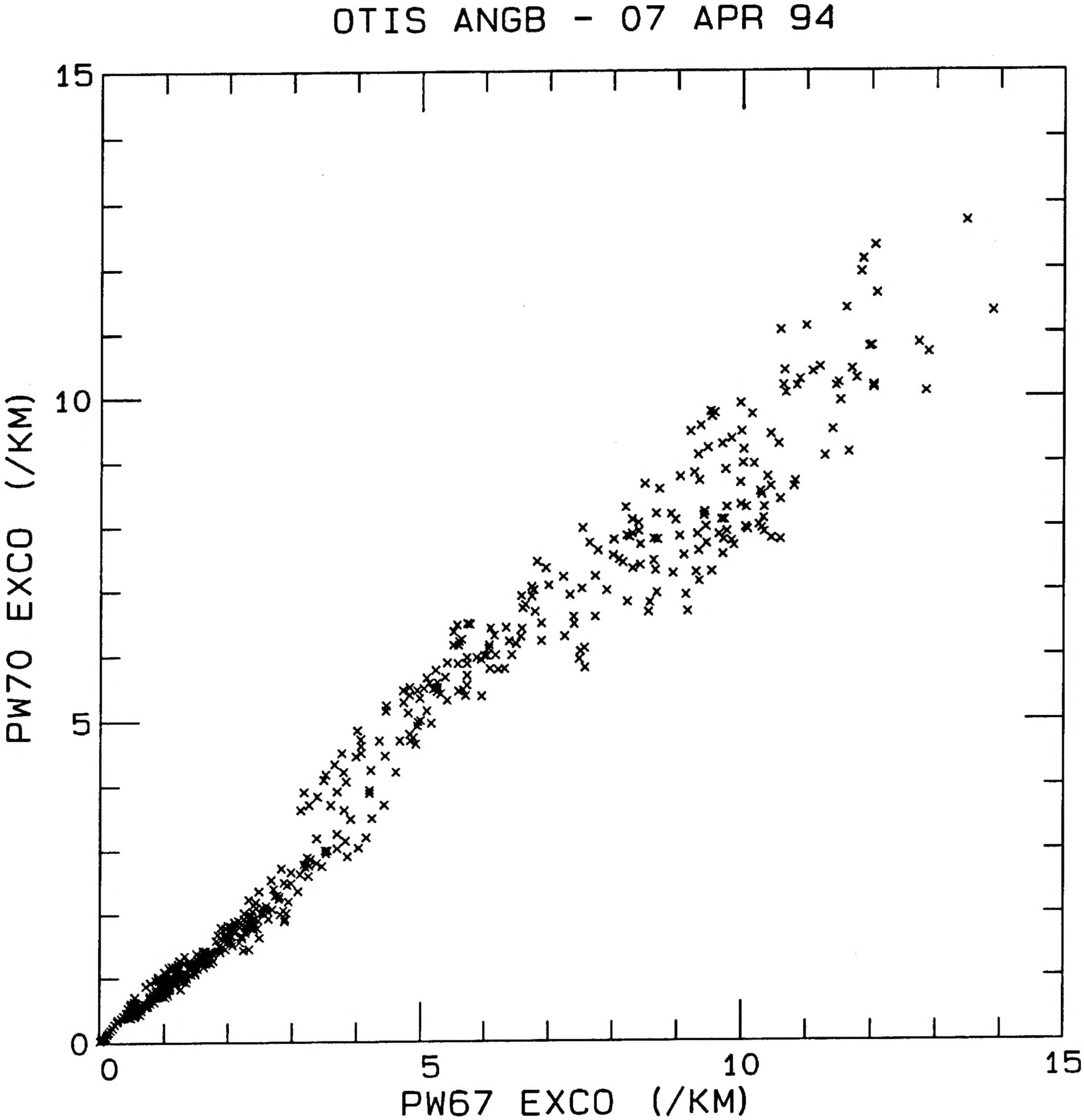


Figure 14 Comparison of EXCO Measurements; VPF-700 vs. PW67; Rain Episode of 7 April 1994.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In broad terms the goals of the program were two-fold: (1) to develop a compact lightweight, robust present weather sensor for Air Force applications, and (2) to retain the performance characteristics of larger HSS, Inc present weather sensors, except for minor compromises in accuracy at high visibilities and in the measurement of the diameter of small drizzle particles.

Some loss in accuracy at these two measurement extremes was expected because the tactical sensor used a 10-bit A/D converter rather than a 12-bit A/D converter as is used in larger HSS, Inc sensors. The 10-bit A/D was an integrated function of the Intel 80C196 microcontroller employed in the tactical sensor electronics. The 80C196 also included analog input and communication features. Use of the 80C196 was justified because its integrated functions permitted a substantial reduction in size of the data processing and communication electronics, an essential step toward overall reduction in size of the sensor. Test results have demonstrated that in practice use of a 10-bit A/D converter has a near-negligible effect on the desired sensor performance.

Performance of the tactical sensor was tested by comparison of its measurements with those of appropriate meteorological instruments under a full gamut of weather conditions at the Air Force Weather Test Facility on Cape Cod. Sufficient comparison tests were made to assure that the design goals had been achieved.

5.2 Recommendations

Upon successful completion of the development and testing of the prototype tactical present weather sensor, the logical next step would be the fabrication of an engineering production model of the sensor. An engineering production model of the sensor should finalize all details of the sensor configuration, incorporating any mechanical and electrical retrofits made to the prototype sensor during the performance testing phase, or any minor design modifications which in hindsight could enhance its operation and maintenance.

Only three such modifications to the prototype tactical present weather are worth noting: (1) the circuit board layouts should be revised to eliminate the small number of cuts and jumpers which seem to be inevitable in prototype instruments, (2) the accessory for supporting the backscatter receiver during calibration checks should be

redesigned to locate and orient the backscatter receiver in a positive fashion, and (3) a conversion to operation from AC-line power instead of battery power should be effected to fulfill the change in the Air Force requirements which come late in the fabrication phase of the sensor.

The result of converting to AC-line power could be the addition of significantly more power to the de-icer hood heaters and provision for permanently powering the no-dew window heaters of the sensor. In the battery-powered sensor, there are three window heating modes available to an operator: (a) always "On", (b) always "Off" and (c) "On" only when dew is sensed by the window contamination monitor and microcontroller. These three modes are provided for power conservation purposes.

The software for the tactical present weather sensor is basically identical to the software employed in the larger model HSS, Inc sensors. That software recognizes all forms of frozen precipitation (snow, snow grains, snow pellets, ice crystals, ice pellets, hail) are identified as snow.

Each sample time period the sensor collects a large amount of particle size/velocity data during a precipitation episode. Inherent in this data is statistical information for characterizing the "signature" of each type of frozen precipitation. This potential addition to the sensor capabilities would require an expansion of both the software and electronic structure. Nevertheless, the probability is high that such modifications could be accomplished within the envelope of the present sensor.

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